

Anisotropic thermoelectric effect in helimagnetic tunnel junctions

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Abstract

Thermoelectric transport across normal-metal/helical-multiferroic/ferromagnetic heterojunctions is theoretically investigated. We find an anisotropic charge and spin thermopower with a C_{2v} symmetry. The angular dependence on the magnetization orientation of the ferromagnetic layer is substantiated by a phenomenological theory based on the symmetry of the effective spin-orbit interaction induced by the topology of the spiral magnetic order in the multiferroic barrier.

With the recent advances in fabrication, patterning and measurement techniques of artificial nanostructures, thermoelectricity has gained renewed interest with a particular focus on potential applications [1–3], specially for the development of electronic devices with low power consumption. Thermoelectric transport is well studied theoretically and experimentally for a variety of systems such as quantum dots [4, 5], molecular junctions [6], and magnetic tunnel junctions [7–9]. Recently, a qualitatively original phenomena, the Spin-Seebeck effect, was discovered by Uchida *et al.* [10, 11]: In a ferromagnetic material ($\text{Ni}_{81}\text{Fe}_{19}$) a heat current leads to a pure spin current without a charge current. This surprising effect has by now been confirmed experimentally for insulating ferrimagnets ($\text{LaY}_2\text{Fe}_5\text{O}_{12}$ in [12]), and for ferromagnetic semiconductors (GaMnAs [13]) as well. In these experiments, the spin-Seebeck coefficient was found to be quite smaller than the charge-Seebeck coefficient. However, in contrast to bulk ferromagnets, the spin thermopower in a quantum dot is theoretically predicted to be on the same order of magnitude as the charge thermopower [4, 5]. Along this line we inspect in this work the thermoelectricity in a normal-metal/helical-multiferroic/ferromagnetic heterojunctions such as $\text{Pt}/\text{TbMnO}_3/\text{SrRuO}_3$ (cf. Fig.1). The coexistence of coupled electric and magnetic order parameters in multiferroics [14] holds the promise of futuristic opportunities for spintronics devices [15, 16] with the particular advantage of being electrically [17] and/or magnetically [18] controllable. The essential point is that due to the topology of the local magnetic moments in multiferroic insulator, a traversing carrier experiences an effective spin-orbit interaction [16]. As shown by Hatimi *et al.* [8], the thermoelectric effects significantly depend on the relative angle of the magnetization in neighboring magnetic layers of the ferromagnetic/normal-metal/ferromagnetic heterojunctions. Moreover, in the presence of the spin-orbit interaction, we expect that the tunnel magnetoresistance should show a spatial anisotropy in a ferromagnetic/insulator/normal-metal heterojunction [16, 19, 20]. Similarly, we find that the non-collinear magnetic order in the oxide together with the induced spin-orbit coupling result in uniaxial spin and charge thermopower with a C_{2v} symmetry.

A sketch of the system is shown in Fig.1. A magnetic tunnel junction consisting of an ultrathin helical-multiferroic (MF) barrier (usually an oxide) is sandwiched between a normal metal (NM) lead and a ferromagnetic (FM) conductor. No voltage is applied across the junction. A steady temperature difference ($T_{NM} \neq T_{FM}$) between the FM and NM electrodes is induced. As the transmission is spin dependent, the temperature gradient may

lead to a spin accumulation in the electrodes, which generally results in a nonzero spin-voltage bias $\Delta V_s = (\delta\mu_{FM} - \delta\mu_{NM})/e$, where e is the electron charge and $\delta\mu_i = \delta\mu_{i\uparrow} - \delta\mu_{i\downarrow}$ with $\delta\mu_{i\sigma}$ being the electrochemical potential of the spin σ to the right or to the left of the oxide barrier. In the linear response regime (which is assumed here), the spin dependent current is written as [7],

$$I_\sigma = eL_{0\sigma}\Delta\mu_\sigma + \frac{e}{T}L_{1\sigma}\Delta T \quad (1)$$

where $\Delta\mu_\sigma = e\Delta V_\sigma$ is the difference in the chemical potentials of the two leads in the spin channel $\sigma = \pm 1$ (or $\uparrow\downarrow$), and $\Delta V_\sigma = \Delta V_e + \sigma\Delta V_s$ with ΔV_e being the charge bias. ΔT is the applied temperature difference. The kinetic coefficients $L_{n\sigma}$ are defined as [21]

$$L_{n\sigma} = -\frac{1}{\hbar} \int \frac{dE}{2\pi} (E - \mu)^n T_\sigma(E) \frac{\partial f(E)}{\partial E} \quad (2)$$

where $f(E)$ is the Fermi-Dirac distribution function. $T_\sigma(E)$ is the spin-dependent transmission probability through the tunnel junction. The charge and the spin current are thus given as $I_e = I_\uparrow + I_\downarrow$, $I_s = I_\uparrow - I_\downarrow$, respectively. We assume the spin-orbit interaction in the *electrodes* to be negligible, hence the two spin channels are independent. A nonzero spin current can be driven by the temperature difference through the system in absence of a charge current $I_e = 0$ as observed in the spin-Seebeck effect [10]. In the present study, we derive the thermoelectric and thermospin coefficients in the presence of the spin accumulation. To find the spin-dependent Seebeck coefficient S_σ , we inspect the limit of the simultaneous vanishing of both the spin current and the charge current; or equivalently a zero charge current in each spin channel, i.e. $I_\sigma = 0$,

$$S_\sigma = \frac{\Delta V_\sigma}{\Delta T} = -\frac{1}{eT} \frac{L_{1\sigma}}{L_{0\sigma}}. \quad (3)$$

Analogously, the spin thermopower S_s and the charge thermopower are calculated as,

$$S_s = \frac{\Delta V_s}{\Delta T} = \frac{1}{2}(S_\uparrow - S_\downarrow), \quad (4)$$

$$S_e = \frac{\Delta V_e}{\Delta T} = \frac{1}{2}(S_\uparrow + S_\downarrow). \quad (5)$$

Neglecting the relatively much smaller potential modification due to the depolarizing field in the multiferroic barrier, and assuming that the barrier potential has a rectangular shape

with the height V_0 , the Hamiltonian describing the tunneling across the heterojunction reads [16], $H = H_m + H_{MF}$. H_m stands for the itinerant carriers in the two metal electrodes,

$$H_m = -\frac{\hbar^2}{2m_e}\nabla^2 - \Theta(z-d)\Delta\mathbf{m}\cdot\boldsymbol{\sigma} \quad (6)$$

where $\boldsymbol{\sigma}$ is the vector of Pauli matrices, $\mathbf{m} = [\cos\phi, \sin\phi, 0]$ is a unit vector defining the in-plane magnetization direction in the ferromagnet with respect to the [100] crystallographic direction, and Δ describes the Zeeman splitting in the FM electrode. $\Theta(z)$ is the Heaviside step function. m_e is the free-electron mass and d is the thickness of the barrier. In the oxide insulator, the carrier dynamics is governed by the exchange model,

$$H_{MF} = -\frac{\hbar^2}{2m}\nabla^2 + J\mathbf{n}_r\cdot\boldsymbol{\sigma} + V_0, \quad \text{for } 0 \leq z \leq d \quad (7)$$

where m is the effective electron mass of the oxide ($m/m_e \approx 3$). $J\mathbf{n}_r$ is the exchange field, where \mathbf{n}_r is given by the multiferroic oxide local magnetization at each spiral layer (labeled by the integer number l) along the z -axis [22], i.e., $\mathbf{n}_r = (-1)^l[\sin\theta_r, 0, \cos\theta_r]$ with $\theta_r = \mathbf{q}_m\cdot\mathbf{r}$ and $\mathbf{q}_m = [q, 0, 0]$ being the spiral spin-wave vector. In effect the exchange coupling acts on the electron as a non-homogenous magnetic field. Performing a local unitary transformation within the barrier [15], we conclude that the influence of the barrier amounts to the spin-dependent potential

$$H_{SO}^{eff} = \mathbf{w}(\theta_r, \mathbf{k})\cdot\boldsymbol{\sigma} \quad (8)$$

where

$$\mathbf{w}(\theta_r, \mathbf{k}) = [J(z)\sin\theta_r, \tilde{q}k_x, J(z)\cos\theta_r] \quad (9)$$

and $\tilde{q} = \frac{\hbar^2}{2m}q$. This effective spin-orbit interaction results in a tunneling anisotropic magnetoresistance (TAMR) effect[16]. Hence, we can expect a similar anisotropic behavior of the thermopower, as well.

In the present study, we assume a barrier of two to five layers (as in [23]) such that the effective spin-orbit interaction H_{MF}^σ throughout the multiferroic barrier is reduced to the plane of the barrier, $\bar{H}_{MF}^\sigma = \bar{\mathbf{w}}(\theta_r, \mathbf{k})\cdot\boldsymbol{\sigma}\delta(z)$ with $\bar{\mathbf{w}}(\theta_r, \mathbf{k}) = [\bar{J}\sin\theta_r, \bar{q}k_x, \bar{J}\cos\theta_r]$. \bar{J} and \bar{q} are renormalized exchange and resonant spin-orbit coupling parameters, $\bar{q} \approx qdm_e/m$ and $\bar{J} \approx \langle J(z) \rangle_d$ referring to space and momentum averages with respect to the unperturbed states at the Fermi energy. In the following, we treat \bar{J} and \bar{q} as adjustable parameters. The transmissivity of a spin- σ electron through the multiferroic tunnel junctions reads

$$T_\sigma(E, \mathbf{k}_\parallel, \theta_r) = \Re \left[\frac{k_\sigma}{\kappa} |t_{\sigma,\sigma}|^2 + \frac{k_{\bar{\sigma}}}{\kappa} |t_{\sigma,\bar{\sigma}}|^2 \right] \quad (10)$$

where the transmission ($t_{\sigma,\sigma}$ and $t_{\sigma,\bar{\sigma}}$) coefficients can be analytically obtained by solving for the scattering states in the different regions [16]. κ and k_σ are the transverse wave vectors in NM and FM subsystems, respectively,

$$\kappa = \sqrt{E/\frac{\hbar^2}{2m_e} - k_\parallel^2}, \quad (11)$$

$$k_\sigma = \sqrt{(E + \sigma\Delta)/\frac{\hbar^2}{2m_e} - k_\parallel^2}, \quad (12)$$

where \mathbf{k}_\parallel denotes the conserved electron momentum parallel to the junction interfaces.

Introducing the transmissivity $T_\sigma(E, \mathbf{k}_\parallel, \theta)$ into Eq.(2), the kinetic coefficients are rewritten as,

$$L_{n\sigma}(\phi) = -\frac{1}{h} \int dE \frac{d^2 \mathbf{k}_\parallel}{(2\pi)^2} \frac{d\theta}{2\pi} (E - \mu)^n T_\sigma(E, \mathbf{k}_\parallel, \theta) \frac{\partial f(E)}{\partial E} \quad (13)$$

Based on a general symmetry considerations of the spin-orbit interaction[24] and phenomenological calculations [16] the angular-dependence of $L_{n\sigma}(\phi)$ is found to exhibit a two fold symmetry, $\sim \cos 2\phi$. Consequently, the charge and spin thermopower are spatially anisotropic.

We performed numerical calculations for $k_B T = 4meV$ with $\mu = 5.0eV$, $\Delta = 2eV$, $V_0 = 0.5eV$, and $d = 1nm$. Fig.2 presents the dependence of the thermopower on the magnetization direction in the FM electrode. As evident from the numerical results, the spin and the charge thermopower show the C_{2v} symmetry, as follows from the phenomenological model. We note, the spin thermopower S_s is about three orders of magnitude smaller than the charge thermopower S_e , which is different from the case of a quantum dot where S_s can be as large as S_e [4]. S_s changes sign as voltage induced in the minority spin channel is higher. For the charge thermopower, the amplitude of the angular-dependence of S_e is quite small, which is on the same order as the tunnel anisotropic magnetoresistance in Fe/GaAs/Au tunnel junction that have been recently realized experimentally [25]. However, S_s changes with ϕ from positive to negative, we have a quite large tunnel anisotropic spin thermopower, $[(S_s(\phi) - S_s(0))/(S_s(\phi) + S_s(0))]_{max} \approx 18$.

Summarizing, we studied the angular-dependence of the thermoelectric transport through the helical-multiferroic tunnel junctions, both the spin and charge thermopower are found to exhibit an anisotropic behavior due to the spiral magnetic order together with an induced spin-orbit interaction in the multiferroic spacer. Based on the magnetoelectric coupling, the strength of the effective spin-orbit coupling is electrically/magnetically controllable and

thus the spin and charge thermopower in the helimagnetic tunnel junctions. For practical applications a multilayer configuration might be more appropriate to enhance the effect.

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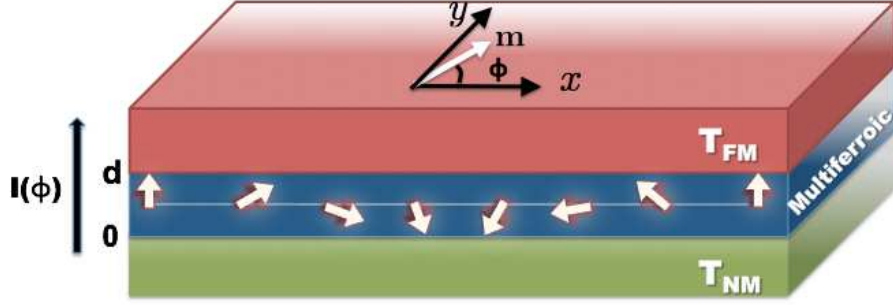


FIG. 1. (Color online) Schematic of a magnetic tunnel junction composed of a multiferroic oxide insulator barrier with spiral magnetic ordering (white arrows), a normal metallic (NM) lead and ferromagnetic (FM) electrode at different temperatures, $T_{\text{NM}} \neq T_{\text{FM}}$. The vector \mathbf{m} indicates the magnetization orientation specified by the angle ϕ in xy (FM) plane with respected to the reference crystallographic axis (x -axis). The zx plane refers to the spiral plane of a multiferroic oxide.

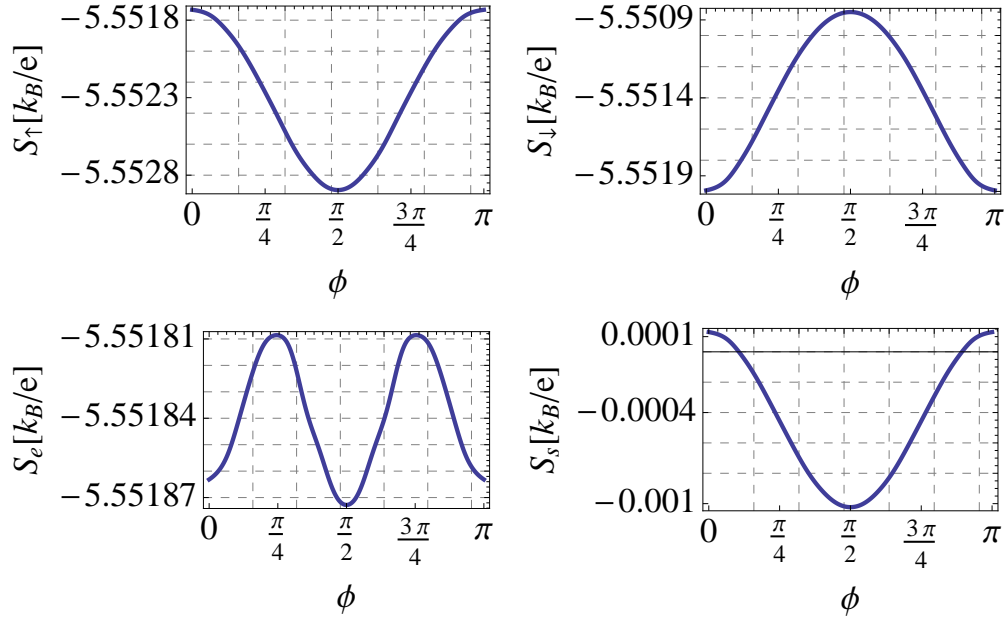


FIG. 2. (Color online) Spin and charge thermopower as a function of the magnetization orientation ϕ in FM layer at $k_B T = 4 \text{ meV}$. Other parameters are chosen as $\mu = 5.0 \text{ eV}$, $\Delta = 2 \text{ eV}$, $V_0 = 0.5 \text{ eV}$, $d = 1 \text{ nm}$, $\bar{J} = 1 \text{ eV}$ and $q = \frac{2\pi}{7a}$ with $a = 5 \text{ \AA}$ being the lattice constant of the oxide.